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Abstract

Beginning in 1922, the rate of exit of U.S. tire producers increased sharply and the industry began a severe and protracted shakeout. Just five years earlier, the tire industry experienced a surge in entry that led to a rise of over 80% in the number of producers. We propose an explanation for this episode based on the idea of industry submarkets, which we incorporate in a model of shakeouts. We test this theory and alternative explanations for the surge in entry and exit and the shakeout using a novel data set on patenting in tires and production in the early 1920s of the cord tire, a key innovation we feature in our theory. Our analysis suggests that the development of a new submarket can open up opportunities for entry but also stimulate innovation and in the process reinforce the advantages of the leading incumbents, accentuating the shakeout of producers.

JEL classification: L65, R12, R30

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I. Introduction

In the United States, the first pneumatic automobile tire was produced by Goodrich in 1896. Twenty one years later in 1917 there were 157 firms producing automobile tires. The next five years witnessed an extraordinary burst of entry, with 249 firms entering between 1917 and 1922, and the number of tire producers peaked at 278 in 1922. Subsequently, the firm exit rate nearly tripled and the number of firms declined sharply despite robust growth in the industry's output through 1929, when the number of producers dropped to 122. The number of producers fell even further after the Great Depression, reaching a low of 49 in 1950. Producers that entered between 1917 and 1922 fared particularly poorly, exiting the industry at a much higher rate than earlier entrants, with over 56% surviving less than five years. How can we explain the extraordinary surge in entry in the industry between 1917 and 1922 in light of the poor subsequent performance of the entrants and the sharp shakeout of producers?

We offer a novel theory to explain this entry episode and the subsequent shakeout in the industry based on the idea of industry submarkets. Industries are often composed of different product variants that appeal to different users and may also require different knowledge and methods to produce, defining distinct "submarkets." Sutton [1998] used the idea of submarkets to develop a theory of firm growth that could explain various regularities in industry firm-size distributions. Klepper and Thompson [2006] used the submarket idea as well to explain regularities in firm growth, entry, and exit, which they applied to explain the steady rise in the number of producers of lasers over the first 35 years of the industry. Bhaskarabhatla and Klepper [2009] crafted a theory around a novel submarket development in lasers to explain both the initial 35-year rise in the number of laser producers and a subsequent shakeout that has caused the number of producers to decline by 50% in the last ten years. Their theory combines the model in Klepper and Thompson [2006] with the model of shakeouts in Klepper [2002] to explain the abrupt change in industry dynamics in the laser industry. In this paper, we pursue a similar tack to Bhaskarabhatla and Klepper [2009] in that we feature the role of submarket dynamics in the tire industry in explaining both the surge in entry preceding the shakeout and then the marked rise in firm exit rates and sharp decline in the number of producers that ensued.

The submarket we feature is based on the cord tire, which was analyzed in Klepper and Simons [2000]. The cord tire was based on a novel design that improved the performance of tires in terms of longevity and dependability. Initially it was particularly appealing to users of large tires, especially truck tires, but for many years the market for the cord was limited by its high price. In addition to its novel design, the cord required distinctive production machinery, which limited the number of cord producers. Indeed, as of 1917, just before the surge in entry, the cord accounted for only 10% of tires sales and only ten firms produced it. Its future prospects were also uncertain, but all this would change in the next six years. Driven by both product and process innovation, the share of sales accounted for by the cord climbed to nearly 50% by 1922 and then an unexpected breakthrough led to the cord taking over the entire industry within a few years. We develop a variant of the model of shakeouts in Klepper [2002] to explain how these developments could have accounted for the surge in entry between 1917 and 1922 and the sharp shakeout and rise in firm exit rates that followed.

The model yields a number of distinctive implications regarding how the fraction of firms producing the cord evolved over time, how time of entry was related to cord innovation, and how the timing of adoption of the cord affected firm survival. We test these predictions using a novel data set that combines data on all tire producers with a list of over 12,000 U.S. patents related to tires that were issued between 1900 and 1930 and data on cord production at the firm level between 1917 and 1922. We also use these data to test distinctive implications of three alternative theories of shakeouts developed by Utterback and Suárez [1993], Jovanovic and MacDonald [1994], and Horvath et al. [2001] that can also explain the surge in entry followed by the sharp shakeout and marked rise in firm exit rates in the tire industry. Indeed, Jovanovic and MacDonald's theory was motivated and tested based on the evolution of the tire industry and Horvath et al. [2001] also claimed to explain the key patterns in tires, and we use our augmented data set to revisit their explanations for the shakeout in tires.

The paper is organized as follows. In Section II we present the basic facts about the industry, including the major technological developments in the industry related to the cord tire and to the Banbury Mixer, which was the key innovation featured in Jovanovic and MacDonald's [1994] analysis of the tire industry. In Section III we present our model and its key implications regarding how the cord tire influenced entry, innovation, and survival of tire producers. We also discuss distinctive implications of the alternative theories. In Section IV we test the implications of the various theories. In Section V we discuss our findings and their implications for the role of demand and submarket dynamics in conditioning innovation and market structure.

II. The Evolution of the Tire Industry

The U.S. automobile tire industry began in 1896. *Thomas' Register of American Manufacturers* was used to compile an annual list of pneumatic automobile tire producers beginning with 1905, when *Thomas'* was first published. The entry dates of the initial producers were backdated as early as 1901 based on *Hendricks' Commercial Register of the United States for Buyers and Sellers*. We have made minor changes to the list of producers since it was originally compiled (see Klepper [2002]) based on subsequent information that enabled us to combine different entries and adjust others. The annual number of tire entrants, exits, and producers from 1901 to 1950 is presented in Figure 1.

Figure 1 indicates that entry increased fairly steadily from 1901 to 1913, when 27 firms entered the industry. It remained fairly constant in the next four years and then increased sharply beginning in 1917. From 1901 to 1916, entry averaged about 13 firms per year, but then increased to 42 firms per year from 1917 to 1922. Subsequently, it fell sharply, dropping to 24 firms in 1923, 17 each in 1924 and 1925, and then to only two firms per year from 1926 to 1950. The number of firms followed a similar pattern, rising sharply from 157 in 1917 to a peak of 278 in 1922, after which it fell steadily for 16 years, reaching a low of 49 in 1950. From the outset the industry was dominated by the "Big Four" (U.S. Rubber/Uniroyal, Goodrich, Goodyear and Firestone) and the considerably smaller Fisk. In the 1920s the joint market share of the "Big Four" steadily increased and reached a high of 79% in 1931 (Gettell [1933, p. 97]).

The rise in entry rates was accompanied by a similar increase in the hazard of exit from the industry. The annual percentage of firms that exited the industry never exceeded 13% through 1922 and averaged 7.6% from 1905 to 1922. In contrast, from 1922 to 1930 the exit rate averaged 19.7%. The hazard was particularly high for the firms that entered starting in 1917. On average, firms that entered between 1917 and 1922 survived seven years and firms that entered between 1922 and 1930 survived six years whereas firms that entered before 1917 survived 13 years.

At about the same time that these pronounced changes in the entry and exit rates took place, several major technological developments occurred in the industry. The single most important product innovation in the tire industry before 1930 was the cord tire, which was introduced in the United States in 1910. Like the fabric tire that it came to replace, the cord tire had a carcass made from cotton fabric. However, while a standard fabric of cross woven threads was used in fabric tires, the individual cotton layers of cord tires were constructed from strong parallel threads, with at most a few soft weft threads used to keep the cords in place during tire building (Pearson [1922]). Tires are subject to constant flexing and bending, which generates internal friction and heat. The cord tire reduced the internal friction generated by cross woven threads rubbing against each other, which greatly increased tire mileage and also reduced the likelihood of blowouts.

Initially, the main use of cord tires was for larger tires, where the advantages of cords were most pronounced. This was especially true for truck tires, where fabric tires were unsuitable because internal heat generation limited their dependability. However, fabric tires were less expensive to produce and dominated the automobile tire market. As of 1917, cords accounted for only 10% of tire sales (Gaffey [1940, p. 43]). Producing the cord tire required distinctive machinery (Pearson [1922, p. 459] and it was also necessary to keep up with product and process innovations related to the cord. This limited the number of cord producers, and in 1917 only ten firms in the industry produced the cord (*Tire Rate Book*, September, 1917).

Eventually cord tires would come to dominate the passenger car market, but back in 1917 there was considerable uncertainty concerning the prospects for the cord (Pearson [1922, p. 230]). From 1917 to 1922 the cord made significant inroads into the market, and by 1922 cords accounted for a little over 48% of tires produced (Gaffey [1940, p. 43]). This largely came about through innovation both in the design and production of cord tires (Pearson [1922, pp. 234-246]). Many types of cord designs were developed. Some were built up from multiple plies of woven cord fabrics whereas in others cords were individually applied to the carcass. Cords were rubberized in different ways and cord plies were placed on the tire core in different sequences and angles. On the production side, dedicated machinery was developed for the preparation of cords, the grouping of cords and the construction of cord fabrics, and the application of cords to the tire carcass (Pearson [1922, pp. 459-486]). The transition from fabric to cord tires also necessitated numerous adaptations in standard rubber production machinery such as vulcanizers and calenders.

One of the main challenges regarding the cord tire was how to get rubber to adhere to the cords. Firestone, among others, experimented with different approaches and in 1920 came up with a novel solution, known as gum dipping, in which the cords were immersed in a rubber solution. It substantially reduced internal heat generation and the hazard of ply separation, which increased the ability of the tire to withstand flexing and bending in use. This in turn allowed tire producers to design wider low-pressure “balloon tires” that provided a more comfortable ride (Lief [1951]). Unexpectedly, the balloon tire also greatly increased the tire’s mileage, and by 1925 nearly all tires sold were of the cord design (Gaffey [1940, p. 43]).

In addition to the cord tire and the process innovations directly related to it, there were further pronounced changes to tire production before 1930. Initially, tire making required hard manual labor and considerable skill. Several generations of tire building machines successively reduced the requirements for manual labor and rendered tire production increasingly capital-intensive. There are five stages of production of tires of comparable cost. The most pronounced change to the early phases of the production process was the Banbury Mixer, which was used in the second stage in which rubber is mixed with chemicals. The Banbury Mixer was patented in 1916 by a supplier to the industry, which sold different sizes of the Mixer to tire and rubber producers. It has been argued by some (e.g., Knopf [1945, p. 107]) that the Banbury Mixer along with other advances in production machinery increased the minimum efficient scale of tire plants.

III. Theory

In this section we consider four explanations for the shakeout and related entry and exit patterns in the tire industry.

A. Increasing Returns to R&D and Submarket Dynamics

Klepper [2002] proposed a model of shakeouts based on the idea of increasing returns to R&D. The model assumes a homogeneous industry in which all firms produce a common product. We first present Klepper's model and then sketch out a variant of the model in which a new submarket arises and grows over time, eventually taking over the entire market.

The model is in discrete time. The industry begins in period 0. At this point there is a queue of potential entrants and in each subsequent period a new queue of potential entrants arises. Potential entrants differ in terms of the productivity of their R&D based on their pre-entry experience. Production is subject to constant returns to scale. In each period, firms decide how much R&D to perform, which determines their average cost. The average cost of firm i in period t is specified as $c_{it} = c_t - a_i g(r_{it})$, where c_t is a cost component in period t common to all firms, $a_i \leq a_{max}$ is the productivity of the firm's R&D, which is fixed over time, r_{it} is its R&D in period t, and $g(.)$ is the decrease in average cost from r_{it}, where $g' > 0$ and $g'' < 0$ for all r_{it} to reflect diminishing returns to R&D. Firms are assumed to costlessly imitate all innovations in the prior period, which is modeled as $c_t = c_{t-1} - \max_i\{a_i g(r_{it-1})\}$.

Let q_{it-1} denote the output of firm i in period t-1. Firms grow in each period t subject to a cost of growth that reflects the costs of attracting new customers and assimilating the additional labor and capital needed to grow. The cost of growth is denoted as $m(\Delta q_{it})$, where Δq_{it} is the absolute growth of the firm's output in period t and $m(.)$ is assumed to be such that $m'(0)=0$, $m' \geq 0$ and $m'' \geq 0$ for all $\Delta q_{it} > 0$.

The industry demand curve is fixed over time. Firms take the price in each period, p_t, as given, where price clears the market. They choose r_{it} and Δq_{it} to maximize their profits in period t:

(1) $$\Pi_{it} = [p_t - c_t + a_i g(r_{it})]\,(q_{it-1} + \Delta q_{it}) - r_{it} - m(\Delta q_{it}).$$

A potential entrant in period t enters iff $\Pi_{it} \geq 0$; if it enters, $q_{it-1} = 0$ and Δq_{it} is its initial output. Similarly, an incumbent firm remains in the industry in period t iff $\Pi_{it} \geq 0$.

At first the price is high enough that entry is profitable for potential entrants with sufficiently high R&D productivity, but over time expansion by incumbents and entry drives the price down to where entry by a firm with the maximum possible productivity a_{max} is no longer profitable. At this point entry ceases. But the most profitable firms expand, which pushes down $p_t - c_t$, which in turn causes some firms to exit. It is easy to show (see Klepper [2002]) that in every period firms are larger the earlier they entered and the greater their R&D productivity. The larger a firm then the greater its profits from lowering average cost and hence the greater the amount of R&D it conducts. Consequently, in every period larger firms have greater profit margins, which causes them to expand and take over a larger share of the market at the expense of the latest entrants with the lowest R&D productivity, which exit. Thus, once entry ceases, the number of firms declines over time—i.e., a shakeout occurs.

Suppose that initially firms produce only fabric tires because the price of the cord tire relative to the fabric tire is too high for anyone to buy it, but at some later point the relative price of the cord falls enough that some customers begin shifting to the cord. Furthermore, suppose at this point that the relative price of the cord is expected to fall further, which will cause a certain percentage of the remaining fabric customers (of each firm) to switch to the cord in each period. We assume that if a firm produced the cord as well as the fabric tire, it retains these customers. Otherwise, the customers start buying the cord from other firms; the probability of an incumbent attracting such a "free" customer is proportional to its level of cord production and entrants also have a non-zero probability of attracting a free customer.

In terms of the profits of producers, equation (1) would now contain two terms, one pertaining to the fabric tire and the other the cord tire. We assume that each type of tire is subject to its own cost-reducing R&D. Suppose there is also a lump-sum cost denoted as C for any firm to enter into the cord tire market, which reflects the cost of learning about demand for the cord and also about the design and production of the cord. Further, for simplicity suppose a firm's R&D productivity in the cord tire is the same as its R&D productivity in the fabric tire. Last, suppose that firms differ in terms of how fast they expect the relative price of the cord to decline and thus how fast they expect customers to switch to the cord.

An incumbent producer of fabric tires enters cord production if its expected discounted profits from producing the cord exceed *C*. These profits depend on the firm's expected cord sales in each period and the length of time it expects to produce tires. Both are greater the larger the firm's output of fabric tires, which determines the number of its customers that switch to the cord and thus its cord output. Therefore, all else equal:

Hypothesis 1: Among firms that produced fabric tires before cord sales began (i.e., pre-cord incumbents), the probability of producing the cord tire in any period (after sales of the cord began) is an increasing function of the firm's size.

Could there be entry into cord production once entry had ceased into the fabric segment of the market? We assume that unless there are free customers for the cord, such entry is not profitable. But if some potential entrants expect cord prices to fall faster than some incumbents, the expected profits of entrants could be positive even with incumbents not entering into cord production and freeing up customers for entrants. Sufficient uncertainty concerning the cord tire thus could lead to different expectations and entry occurring—i.e., to a surge of entry. Note that this implies that all entrants will produce the cord tire whereas some incumbents will not. Entrants are always smaller than incumbents with the same R&D productivity. Therefore:

Hypothesis 2: After cord sales begin, among all producers (including both pre-cord incumbents and entrants in the cord era) the probability of a firm producing the cord tire is a U-shaped function of its size and time of entry.

Before the advent of the cord, larger (fabric) producers do more (fabric) R&D, *ceteris paribus*. In turn, a firm's fabric sales determines its cord sales if it produces the cord, and thus larger fabric producers also would be expected to do more cord R&D. All else equal, time of entry determines a firm's size in any given period, hence:

Hypothesis 3: Earlier entrants do more R&D before and after the advent of the cord tire.

Last, after the introduction of the balloon tire in 1923, the cord took over the entire market, which could contribute to a surge in exit among non-cord producers and those that switched later to the cord. Both have smaller cord output than earlier cord entrants and thus would be expected to have a higher hazard of exit than earlier cord entrants. Furthermore, among the earlier cord entrants, the hazard of exit should decline with the size of the firm. This implies:

Hypothesis 4: After cord sales began, the annual hazard of exit from the tire industry should be lower for cord producers. Furthermore, among cord producers, the hazard of exit should decline with the size of the firm, whereas among non-cord producers size should not affect the hazard of exit.

B. Shakeouts and the Minimum Efficient Scale of Production

The second theory we consider is developed by Jovanovic and MacDonald [1994]. Key to this theory are two inventions: the first that starts the industry and a second, called the refinement invention, that serves as the impetus for a shakeout. Both inventions create opportunities for innovation. Innovation is challenging and so the probability of innovating after each invention is less than one. Successful innovators earn profits greater than the next best alternative, but unsuccessful innovators earn 0 profits. The number of entrants after each invention is sufficient that the expected discounted profits from trying to innovate equals the discounted profits from the next best alternative. After each invention, firms that do not immediately succeed at innovation switch to the next best alternative and no further entry occurs. Hence after the initial invention no entry occurs until the refinement invention, at which point there is a "surge" of entry.

The refinement invention increases the optimal output of the firm (eventually decreasing returns limits the size of firms). The industry demand curve is fixed, so if some firms expand then price must fall. It is assumed that price eventually falls to the point where non-innovators are indifferent between staying and exiting. As further firms innovate and expand, some firms must exit to keep the price at a level where the remaining non-innovators are indifferent about staying or exiting. At this point the rate of exit in the industry rises. With all entry occurring immediately after the refinement, as firms subsequently exit then the number of firms falls—i.e., a shakeout occurs. The firms that survive in the post-refinement era are the successful innovators.

Jovanovic and MacDonald [1994] identified the Banbury Mixer as the refinement invention. Therefore, we should expect the following patterns:

Hypothesis 5: Around the start of the shakeout, there should be a rise in innovation related to the Banbury Mixer, with firms in the vanguard of this innovation more likely to survive during the shakeout.

C. Shakeouts and Dominant Designs

The third theory we review is developed by Utterback and Suárez [1993]. The key idea in this theory is that initially users experiment with different variants of a new product and producers experiment with different ways of designing and producing it, but eventually a *de facto* standard emerges for a new product, dubbed a dominant design. Until this occurs, firms do not invest in process innovation or in specialized machinery for fear that it might become obsolete. This leaves open the opportunity for entry based on innovative product designs, and perhaps even rising entry until the dominant design emerges. Then such entry is no longer profitable. At this point firms start investing in process innovation and in production machinery, and those more able to manage the production process survive while others exit, contributing to a rise in exit and a shakeout.

The dominant design need not correspond to a technological breakthrough; it could just be the last piece in a puzzle. An obvious candidate for the dominant design in the tire industry is the balloon tire, which was introduced right around the start of the shakeout in tires. While it was hardly a radical innovation, it led to the dominance of the cord tire and thus a *de facto* product standard. This implies the following patterns:

Hypothesis 6: Around the time of the balloon tire (1923), there should be a sharp rise in process innovation and fall in product innovation.

D. Shakeouts and an Entry Cascade

The last theory is developed in Horvath et al. [2001]. Among theories of shakeouts that do not feature the role of technological change, it is distinctive in that it can readily explain the defining events in tires.

The key idea is that unexpectedly good performance by incumbents can signal favorable conditions for entry that induce a sudden surge of entry. Entrants differ in ability but can only learn their ability through experience, with those that are less able eventually exiting. Hence a surge of entry must be followed by a surge of exit, particularly among the latest entrants. If the surge of entry is unique, then it must be followed by a unique decline in the number of producers—i.e., a shakeout. This suggests that during the shakeout the hazard of exit will be greater for later entrants but will be unrelated to a firm's prowess regarding the cord tire, Banbury Mixer, or process innovation generally:

Hypothesis 7: The hazard of firm exit during the shakeout will be related to the firm's age but not its adoption of or innovation regarding the cord tire, Banbury Mixer, or the production process writ large.

IV. Empirical Results

The hypotheses are evaluated in the order in which they are numbered. The first two hypotheses pertain to the rate of cord production by firms that entered before the advent of the cord market and by all entrants, including those that entered in the cord era. Information about firm production of the cord tire was taken from *Tire Rate Book* (*TRB*), a quarterly trade journal catering to the needs of tire dealerships. The earliest surviving issue of the *TRB* is September 1917, when ten firms were recorded as producing the cord, and the next surviving issue in July 1918 lists 24 cord producers. The next extant issue for October 1920 is quite different. It lists 162 firms that show up in our list of tire producers (based on *Thomas' Register*), of which 122 are listed as producing the cord. We use this information about firm cord production to evaluate hypotheses 1 and 2.[1]

Table 1 presents the rate of cord production by time of entry and firm size, where the former is based on the first edition of *Thomas' Register* in which a firm shows up and the latter is based on the firm's capitalization reported in *Thomas' Register* for 1920 or 1922 if the firm first showed up in *Thomas' Register* in 1922 (no edition of *Thomas' Register* was published in 1921). The capitalization data are reported in eleven intervals; the top interval of $1,000,000 and above is open-ended and one interval is reserved for firms with unknown capitalization, which usually turn out to be among the smallest firms once their capitalization becomes known (as reflected in a later issue of *Thomas' Register*). We maintain these two intervals as separate categories and arbitrarily divide the rest of the firms into those with a capitalization above and below $300,000. We group the entrants into three cohorts in terms of their time of entry. We noted earlier that as of 1917 only ten firms produced the cord tire, and two years earlier the cord accounted for only 5% sales of all tires (Gaffey [1940, p. 43]). Accordingly, we assume that firms that appeared in *Thomas' Register* before its 1915 edition (this includes some firms whose entry was backdated as early as 1901) entered before the cord market began in earnest and thus constitute the pre-cord incumbents of hypothesis 1. We divide the rest of the entrants arbitrarily into those appearing initially in the 1915-1919 editions of *Thomas' Register* and those appearing initially in the 1920 and 1922 editions of *Thomas' Register*.

Hypothesis 1 predicts that among the pre-cord incumbents, the probability of producing the cord should rise with firm size. While 86% of the entrants prior to 1915 produced the cord tire as of the 1920 *TRB* and over 75% of these firms had a capitalization of $300,000 or higher (in 1920), the rate of cord production was 70% for the firms with less than $300,000 in capitalization versus 93% for those with a capitalization of $300,000 to $1,000,000 and 89% for those with capitalization of $1,000,000 and above. Although the sample is too small for these differences to be statistically significant at conventional levels, they are substantial and consistent with hypothesis 1.

Hypothesis 2 predicts a U-shaped pattern between the probability of cord production and time of entry and firm size among all cord producers. The last column and row of Table 1 report the rates of cord production among all entrants broken down into the four size categories and three entry cohorts. Overall, 75% of the 162 firms produced the cord. Among the 43 entrants in 1901-1914, this fraction is 86%, which declines to 69% for the 78 entrants in 1915-1919 and then rises to 76% for the 41 entrants in 1920-1922, consistent with hypothesis 2. In terms of firm size, the later entrants were considerably smaller than those that entered before 1915 (and were still in the industry in 1920), as the theory predicts. But their greater rate of cord production, particularly in the smaller size categories, gives rise to the predicted non-monotonic pattern. Among the 37 firms in the top capitalization interval of $1,000,000 and above, 81% produced the cord. This declines to 74% for the 43 firms in the $300,000 to $1,000,000 category and then declines again to 69% for the 51 firms in the $10,000 to $300,000 category before it rises to 81% for the 31 firms in the unknown category. While the sample size is too small for

[1] The firm sample is slightly larger than that of 155 used in Klepper and Simons [2000] because further research on the industry allowed us to clarify the identity of some additional tire producers.

these differences to be significant at conventional levels, the differences are substantial and accord with hypothesis 2.

The theory attributes these patterns to the cord providing opportunities for later entrants. Consistent with this, 14 of the entrants listed in *Thomas' Register* in 1917 or later have "cord" as part of their name, such as Carlisle Cord Tire Co. of Andover, MA, which first appeared in the 1918 edition of *Thomas' Register*.[2] Indeed, we know that some of the most successful entrants of this time capitalized on the cord tire. Perhaps the most striking case is the Denman-Myers Cord Tire Co., an Ohio firm co-founded by Walter Denman, who had previously designed the cord tire produced by Miller Rubber Co. of Akron and assigned multiple tire design and machinery patents to them before organizing Denman-Myers in 1919. Furthermore, around 1920 a substantial number of entrants are announced in the trade journal *India Rubber Review (IRR)* as specializing in cord tire production.[3] This is also reflected in the firm price lists published in the October 1920 and October 1922 issues of the *TRB*. The October 1922 issue lists 31 producers that only made cord but not fabric tires, nearly all of which entered after 1915.

Hypothesis 3 pertains to firm R&D efforts before and after sales of cord tires began in earnest. We test these predictions using a novel data set we assembled on tire-related patents that were listed monthly in *India Rubber World* (*IRW*), another trade journal covering the rubber and tire industries. The full list contains 24,934 rubber and tire-related patents issued between 1901 and 1930 and includes the patent number, inventor name(s) and location(s), individual and corporate assignee(s) (if any), and a short description of the patent, to which we added the USPTO classes pertaining to each patent. We excluded patents granted to non-U.S. inventors and patents related to rubber

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[2] Other examples include Archer Cord Tire & Rubber Co. (Minneapolis, MN; first listed in 1917); Iowa Cord Tire Co. (Des Moines, IA; 1919); Cord Tire Corp. (Chester, W.V.; 1920); and Interlocking Cord Tire Co. (Akron, OH; 1920).

[3] Examples include Erie Tire & Rubber Co. (Cleveland, OH; announced in IRR 1919, pp. 247; 708); Master Tire & Rubber Co. (Dayton, OH; IRR 1919, p. 390); Zenith Tire & Rubber Co. (Cleveland, OH; IRR 1919, p. 602); Parker Tire & Rubber Co. (Indianapolis, IN; IRR 1919, p. 883). Entry opportunities were also created in upstream markets, as illustrated by the case of Allsteel Ridewell Tire & Rubber Co. This firm, whose founder had previously worked for Goodrich and Firestone, marketed an all-metal collapsible core for cord tire building.

goods but not tires based on the primary classes of each patent,[4] which reduced the list to 12,610 U.S. tire-related patents. Of these, 4,407 have a corporate assignee and 2,264 of these were assigned to one of the tire firms in our list (based on *Thomas' Register*).[5]

Hypothesis 3 is evaluated using Table 2, which presents the share of the 2,264 patents that were assigned to Goodrich, Goodyear, U.S. Rubber, Firestone, and Fisk, which were among the earliest entrant in the industry and were the five largest producers in the industry from early on (before 1910). The patents are divided into the three decades of 1901-1910, 1911-1920, and 1921-1930 to reflect the evolution of the shares of patenting of the leaders. Also reported is their joint market share in each decade compiled from various sources. In the first decade, the five firms accounted for 77.2% of the patents versus a combined market share of 54%. Goodrich, which was the early leader of the industry, accounted alone for 42% of the 96 patents issued in this era. The share of patents accounted for by the five firms rose to 76.5% of the 519 patents issued in 1911-1920 compared to their joint market share of about 64%. Goodrich's share of patents declined and the share of the other four firms increased, which corresponds with the decline in Goodrich's market share at the expense of the other four firms.[6] The joint share of patents of the top five firms continued to rise into the 1921-1930 decade, when they accounted for 80.7% of the 1,649 patents issued compared to their joint market share of 66%. U.S. Rubber did not fare well in this period in terms of market share, dropping from 11.3% of the market in 1917 to 6.6% in 1929.[7] This is reflected in its share of patents, which dropped from 17.9% in 1911-1920 to 6.7% in 1921-1930. Fisk became the leading patenter in this period, which was unexpected given that its market share did not increase appreciably from the earlier decade.[8]

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[4] We checked this categorization relative to a manual one we developed based on the description of the patent, which yielded an overlap of 93%.

[5] The share of assigned patents is comparable to other patents in the time period (cf. Lamoreaux et al. [2007]).

[6] Blackford and Kerr [1996] discuss the reasons for Goodrich's decline in the 1910s.

[7] U.S. Rubber originally was a footwear trust that entered the tire business in 1905 by acquiring the Rubber Goods Manufacturing Co., a trust of rubber and tire producers organized in 1895. Its individual tire businesses, G&J, Hartford Rubber Works, and Morgan & Wright, remained largely independent until 1917, and the ensuing centralization attempts caused severe management problems (Babock [1966]).

[8] To some extent, the increase in Fisk's patenting after 1920 seems to reflect its 1920 acquisition of Federal Rubber Co. of Cudahy (WI), as more than 30% of its 1921-30 patents have inventors living in Wisconsin.

Thus, consistent with hypothesis 3, the leading firms dominated patenting both before and after the advent of the cord tire. Furthermore, their shares tended to rise and fall with their market shares, as would be expected based on our model. Overall, only 75 firms out of the 530 that entered through 1930 were ever assigned one or more patents. In addition to the five leading firms only seven other producers were assigned 10 or more patents, and these seven were concentrated among the earlier entrants.[9] Consistent with hypothesis 3, this suggests that efforts devoted to technological change were heavily concentrated among the largest firms in the industry, which were among the earliest entrants. Indeed, Warner [1966] compiled a list of major tire innovations over the period 1895 to 1965, and nearly all of these innovations that were attributed to tire firms were accounted for by the Big 4 of Goodrich, Goodyear, U.S. Rubber, and Firestone. Below we report figures on patents related to the cord tire, and it will come as no surprise that they too were dominated by the Big Four and Fisk.

The last hypothesis of our theory, hypothesis 4, predicts that after the advent of the market for the cord tire, the hazard of firm exit is related to the time when firms began producing the cord. Similar to Klepper and Simons [2000], for the 162 producers in the 1920 *TRB* that are also listed in *Thomas' Register* we use the data on cord production from the 1920 *TRB* and their date of exit based on *Thomas' Register* to test hypothesis 4. Table 3 reports the coefficient estimates of various Cox proportional hazard models of the annual hazard of exit after 1920. The first model contains just a single dummy variable equal to 1 for firms that produced the cord in the 1920 *TRB*. The coefficient estimate of the dummy is negative and significant at the .01 level, consistent with hypothesis 4. It implies a 52% lower annual exit rate for cord producers.

In Model 2 we divide the cord and non-cord producers into three size categories according to whether their capitalization in 1920 exceeded $300,000 (*topsize*), was between $25,000 to $300,000 (*midsize*), or was below $25,000 or unknown (*smallsize*).

Fisk's market shares may thus have been underestimated, but even accounting for Federal's output, Fisk surely did not reach the size of the other leading firms.

[9] The seven firms are Kelly-Springfield (entry year 1902: 40 patents), DeLaski-Thropp (1906: 14), Republic (1907: 12), Hood (1911: 106), Miller (1915: 109), India (1919: 16), and Lambert (1919: 30). Between them, the 12 leading patenters accounted for more than 92 per cent of all patents assigned to tire producers.

We allow each group of firms to have a different hazard (*smallsize* non-cord producers are the omitted group) to test whether the hazard of exit was related to size among cord producers but less so among non-cord producers, as predicted in hypothesis 4. We also control for the firm's time of entry by including the log of its age in 1920 as an explanatory variable. The estimates reflect the predicted ordering among the cord producers, with the largest cord producers having the lowest hazard, followed by the middle-sized cord producers and then the smallest cord producers. These differences are large and significant.[10] In contrast, size has little effect on the hazard of the non-cord producers, consistent with hypothesis 4. The estimates imply that the hazard of exit of the smallest cord producers is less than the hazard of exit of all sizes of non-cord producers,[11] which reflects the influence of cord production on firm longevity.

Hypothesis 5 concerning the role of the Banbury Mixer in the shakeout comes out of Jovanovic and MacDonald's [1994] model. If the Banbury Mixer opened up a new trajectory of challenging innovations that determined firm survival during the shakeout, then we might expect to see a surge of patenting among tire producers related to the Banbury Mixer around the start of the shakeout. To test for this, we first checked for patents in our list with the word Banbury in the description, but found none. Then we used Google Patents to search for patents that in their full text mentioned "Banbury," "rubber mixer," or finally just "rubber mixing." There were 17 patents in our list between 1916 and 1928 that referred to Banbury. Fernley Hope Banbury, who invented the Banbury Mixer, was the inventor of 15 of them, and 14 of these were assigned to Banbury's employer, the Birmingham Iron Foundry, or its successor, the Farrell Birmingham Co.[12] There were 21 patents issued between 1920 and 1927 that referred to rubber mixer, and all but one was assigned to Farrell Foundry Co., the firm with which Birmingham merged in 1927 to form Farrell Birmingham (Killeffer [1962, p. 67]).[13]

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[10] The estimates suggest that cord producers in the largest size bracket had a 32% lower hazard than those of medium size and a 43% lower hazard than those in the smallest size category. The difference between cord producers of the largest and the smallest sizes is significant at the .05 level while the difference between the largest and the medium-sized cord producers is significant at the .13 level.

[11] For example, the annual hazard of exit is 35% lower for the smallest cord producers than the largest non-cord producers.

[12] The remaining two patents were unassigned patents by inventors from Massachusetts and California.

[13] The other one was a 1927 patent assigned to the Naugatuck Chemical Co.

Last, there were 58 patents that referred to rubber mixing, of which 16 (issued between 1916 and 1929) were assigned to tire producers on our list.[14] Only six of these patents, however, were granted before 1925, which is certainly a small number if the Banbury Mixer was responsible for the waves of entry and exit in the early 1920s.

We used the same methods to trace the role of the cord tire in the innovation process. We found 132 patents with "cord" in the brief description given in the *IRW* listing. A Google Patents fulltext search for "cord tire" yielded 152 *IRW*-listed patents, 35 of which were granted before 1920, 39 between 1920 and 1922, and 33 between 1923 and 1925. A total of 65 of these patents were assigned to tire producers on our list, of which 43 were granted by 1925. Among the 65 patents, the five firms with the most patents were the top five all-time patenters: Fisk had 17, Goodyear 16, Goodrich 11, U.S. Rubber five, and Firestone four.[15] These patterns are consistent with Pearson's [1922] discussion of the extensive patenting that took place both in cord designs and cord-related production machinery before 1922. Consistent with the analysis of the influence of cord production on the hazard of exit, they suggest that the cord tire had much greater ramifications and posed much greater innovative challenges than the Banbury Mixer. Indeed, the supplier of the Banbury Mixer, Birmingham Iron Foundry, not only sold the Mixer but it also helped purchasers adapt the Mixer to their production process (Killeffer [1962, pp. 108-118]), which appears to have limited their need to innovate to accommodate the Mixer.

Hypothesis 6 pertains to Utterback and Suárez's theory of shakeouts based on the idea of a dominant design, which is expected to shift the locus of innovation from product to process innovation once it emerges sometime around the start of the shakeout. We test this hypothesis by breaking up all the patents into four categories based on their primary patent classes and subclasses: product patents, process and machinery patents, chemical and machinery patents, and patents on tire-related devices such as pumps and air pressure

[14] Four of the patents were assigned to B.F. Goodrich and four to Goodyear, followed by U.S. Rubber and Miller with two each and Fisk, Gillette, Kelly-Springfield and Norwalk with one each.

[15] It is notable that 10 or 59% of Fisk's cord-related patents were granted after 1925 whereas all of U.S. Rubber's cord patents and most of Goodyear's (12 or 75%) and B.F. Goodrich's (9 or 82%) were granted by 1925.

gauges.[16] Figure 2 plots the annual number of patents for 1901-1930 and breaks them down into the four categories. The number of patents increased sharply until 1915 or so and then leveled off. This rise was largely driven by an increase in product patents. After 1913 the number of product patents begins to decline and falls off sharply in the 1920s, but this is made up by the sharp rise in process and machinery patents beginning in 1913, well before the start of the shakeout.

Figure 3 presents the annual number of product and process and machinery patents assigned to tire producers over the period 1901-1930. The total number of assigned patents rises, particularly after 1910, until the very end of the period. The number of product patents peaks in 1916 whereas the number of process and machinery patents rises steadily and sharply from 1910 on, surpassing the number of product patents by 1915. The timing of this rise accords with data on labor productivity, which indicates that the greatest rate of labor productivity advance among all industries in the period 1914 to 1927 was in the tire industry (Gaffey [1940, p. 81]).[17] Most importantly, it indicates that increasing efforts were devoted to the production process as far back as 1910, which is well before the start of the shakeout in tires. If the returns to process innovation were more dependent on firm size than the returns to product innovation as modeled in Klepper [1996] and supported empirically in Cohen and Klepper [1996], these trends would be consistent with the emphasis in our model on the importance of firm size in conditioning the returns from R&D. They are clearly not consistent with a shift from product to process innovation commencing sometime around the start of the shakeout, as predicted in hypothesis 6.

The last hypothesis comes out of Horvath et al.'s [2001] model of shakeouts and concerns the factors underlying the hazard of exit during the shakeout. It predicts a lower hazard of exit among older producers, which is consistent with the negative and significant coefficient estimate of log age in Model 2 in Table 3. However, hypothesis 7

[16] This categorization is based on the patents' primary USPTO classes and subclasses. In later years, process, machinery and chemical patents were separately listed in the *IRW*. We used information on the USPTO classes of these later patents to assign USPTO classes to the four categories and then classified the earlier patents according to their USPTO classes.

[17] This is quite impressive given the revolutionary developments in mass production that were taking place contemporaneously in the automobile industry, which was the number two industry in productivity advance.

predicts that the hazard of exit will not be related to any technological factors, yet we have seen that it was highly related to cord production, and among cord producers to the size of the firm, as predicted in hypothesis 4. To check that these findings apply to the later entrants during the shakeout, we re-estimated Model 1, which only contains the 1-0 dummy for cord production, for just the entrants after 1917 over the period 1920-1935.[18] The coefficient estimate for the cord dummy, which is reported in the last column of Table 3, is negative and significant at the .05 level and implies a 40% lower hazard of cord producers. Thus, it would appear that the performance of later entrants during the shakeout depended on mastery of the cord tire, which is not consistent with hypothesis 7.

V. Discussion

In its formative era, the tire industry was a high-tech industry. Originally, the average life time of tires was only a few hundred miles (French [1991, p. 15]), but through continual product innovation it increased to 2,000 miles by 1905, 3,000 miles by 1910, 5,000 miles by 1920, 10,000 miles by 1925, and 15,000 miles by 1930. Coupled with great advances in the production process, this caused the price per tire mile to fall by 92.6% from 1914 to 1929 (Gaffey [1940, pp. 39, 131]).

Various books and theses document the continual stream of innovations introduced by tire companies. The series we put together on patents indicates the great deal of attention that was devoted to technological change in tires by both individuals, tire producers, and other firms, such as tire machinery producers. There is little doubt that the leading tire producers, most notably Goodrich, Goodyear, U.S. Rubber, Firestone, and Fisk, were in the vanguard of tire innovation throughout the first 35 years of the industry. They accounted for nearly all the major innovations developed by tire producers in this period (Warner [1966, p. 4]), which is not surprising given their dominance of patenting. Indeed, it is remarkable how few other firms participated in patenting given the large number of firms that entered the tire industry through 1930.

Given the importance of technological change in the tire industry, one would be hard pressed to explain the major developments that took place in the industry in terms of

[18] Firms that had not exited by 1935 were treated as censored. With only 87 observations, most of which

its market structure without reference to technological change. Causality cannot be easily teased out, but it would appear that the early large market share captured by Goodrich, Goodyear, U.S. Rubber, Firestone, and Fisk enabled them to remain on top of the industry for its first 35 years. Over time their market share steadily increased toward their share of patents, suggesting that technological change played a key role in their dominance of the industry. The model of industry evolution developed by Klepper and adapted by us certainly is consistent with these patterns. Moreover, if it is assumed that size conditions the returns to process more than product innovation (cf. Klepper [1996]), then the long-term rise in process relative to product innovation that we date as starting around 1910 can also be readily accounted for by the theory.

It would seem that related forces must have played a role in the shakeout of tire producers and the evolution of its oligopolistic market structure. But can technological change also explain the extraordinary surge in entry that occurred from around 1917 to 1922 and the subsequent sharp rise in firm exit rates, which on its own could explain the shakeout in tires, at least for its first five years or so? The shakeout lasted a lot longer than five years, however, so it might be suspected that the surge in entry and subsequent surge in exit was part of a broader process related to technological change.

We considered three different theories about how technological change could have contributed to the surge in entry and subsequent rise in exit rates in the 1920s. All three feature particular technological developments: the cord tire, the Banbury Mixer, and a rise in process relative to product innovation. Only our theory positions its featured technological development, the cord tire, within the broader context of technological change that characterized the industry before, during, and after (the bulk) of its shakeout. Our analysis of patents related to the Banbury Mixer versus the cord tire suggests that the ramifications of the Banbury Mixer paled relative to the cord tire. Indeed, it is hard to see changes in the minimum efficient scale of production related to the Banbury Mixer or any other innovation on their own causing the extreme fall in the number of producers and evolution of oligopoly that characterized the industry. By all accounts, the leading firms were far bigger than needed to achieve minimum efficient scale (Reynolds [1938], Knopf

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were in the smaller size classes, it was not feasible to break down the firms by size.

[1949]). As Bain [1956] concluded many years ago, scale economies in production do not seem to be able to explain very well variations across industries in their market structure.

The idea that new products evolve toward a dominant design, which is a watershed in terms of product and process innovation and possibly industry structure, has long been popular. Data to test for the predicted shift from product to process innovation have always been elusive, though, reflecting both the difficulty of distinguishing the two types of innovation but even more so the difficulty of doing so over long periods of the evolution of industries. Our data provide a unique opportunity to assess the predictions of the theory for tires. By all accounts, process innovation rose markedly in the tire industry as early as 1910, well before any kind of candidate for a dominant design and well before the shakeout began in tires. Indeed, it would seem that the typical normative prescription of the theory, namely wait until product innovation has slowed down to invest in the production process, was not followed. As such, it is hard to see the emergence of a dominant design as a watershed that led to the shakeout in tires.

But could the cord tire have alone galvanized the great surge in entry that occurred in the industry? If so, it does not seem like much of a reach to think that it also caused the surge in exit that followed given the unexpected takeover of the entire industry by the cord tire that was driven by the development of the balloon tire. The original model developed by Klepper [1996, 2002] cannot readily account for such a surge in entry—it does not predict that entry will surge just before a shakeout. Nevertheless, such surges are common (cf. Horvath et al. [2001], Klepper [2002]). So something more is needed, which we supplied via the idea of a submarket. Industries are commonly composed of different products serving different classes of users, which is precisely how the cord tire began. When submarkets turn out to have greater potential for improvement than was widely recognized at their outset, they can also have dramatic effects on an industry's market structure. Bhaskarabhatla and Klepper [2009] argue this is what occurred in the laser industry. In their model an old submarket unexpectedly became dominant and changed both the character of innovative effort and the industry's market structure. In our model, it was a new submarket that played the key role, but unlike the laser industry the submarket soon became tied to the industry's main submarket. As a result, it did not upset the dominance of the industry by its leaders, but it did seem to open up new opportunities for entrants.

Why would a development like this favor entrants and lead to a surge in entry? In our theory, it is uncertainty that makes some incumbents slow to enter into cord production and thus leaves an opportunity for entrants. New developments, particularly ones that start out servicing a distinctive market, often have a way of surprising industry participants when their potential for improvement turns out to be much greater than anticipated. This is the story Christensen [1993] tells about the disk drive industry. Incumbents did not recognize the far reaching implications of smaller disk drives, which not only appealed to buyers of new types of computers but turned out to capture the demand of the users of the old machines as well when the new drives were improved over time. In lasers it was not so much that firms did not recognize the potential of the new developments as much as the developments ended up favoring one type of laser producer. Was there a parallel that occurred in tires that greatly stimulated entry? The record indicates that the later entrants were intensively involved in the cord tire and that early production of the cord tire was closely related to the subsequent survival of producers after the cord market took off, consistent with the cord opening up new opportunities for entrants.

We close by tying innovation back to demand. Submarkets by their very nature appeal at first to a limited class of buyers. Incentives to improve a submarket's products would seem to turn critically on the size of the demand for the submarket's products. If innovation unexpectedly expands the size of a submarket, it can increase incentives to innovate, which no doubt will stimulate the growth of the submarket. It is not hard to envision how such a self-reinforcing process can lead to a dominant submarket arising or a new dominant submarket replacing an old one. Depending on which firms are favored by these developments, we could witness wholesale turnover in the leaders, as in disk drives, or the reinforcement of the leaders, as in tires. Either way, we might well observe a surge of entry in response to new opportunities, with the long-run ramifications regarding an industry's market structure depending on whether it is the entrants or incumbents that are favored by these developments. Our interpretation of events in the tire industry is that in the end the new submarket reinforced the positions of the leaders, but only after it spurred a great wave of entry and exit.

Table 1: Percentages of Cord Tire Producers by Size and Time of Entry

	1901-14			1915-19			1920+			All years		
	Total	Cord	%	Total	Cord	%	Total	Cord	%	Total	Cord	%
$1,000,000 or larger	19	17	89 %	14	10	71 %	4	3	75 %	37	30	81 %
$300,000 -- $1,000,000	14	13	93 %	20	14	70 %	9	5	56 %	43	32	74 %
$10,000 -- $300,000	10	7	70 %	26	16	62 %	15	12	80 %	51	35	69 %
unknown size.	-	-	-	18	14	78 %	13	11	85 %	31	25	81 %
All size categories	**43**	**37**	**86 %**	**78**	**54**	**69 %**	**41**	**31**	**76 %**	**162**	**122**	**75 %**

(Sources: *Tire Rate Book*, October 1920 issue; capitalization data from *Thomas' Register* 1920-22)

Table 2: Patent Shares (Market Shares) of Leading Tire Firms (in %)

	1901-10	**1911-20**	**1921-30**	**All years**
BF Goodrich (entry: 1901)	41.7 (21)	21.8 (N.A.)	18.4 (7)	20.2
U.S. Rubber (entry: 1901)	11.5 (15)	17.9 (10)	6.7 (7)	9.5
Firestone (entry: 1906)	9.4 (7)	12.1 (14)	14.1 (19)	13.4
Goodyear (entry: 1902)	8.3 (4)	16.4 (25)	20.0 (29)	17.0
Fisk (entry: 1901)	6.3 (7)	8.3 (N.A.)	21.5 (4)	13.4
Total	**77.2 (54)**	**76.5 (64)**	**80.7 (66)**	**77.9**

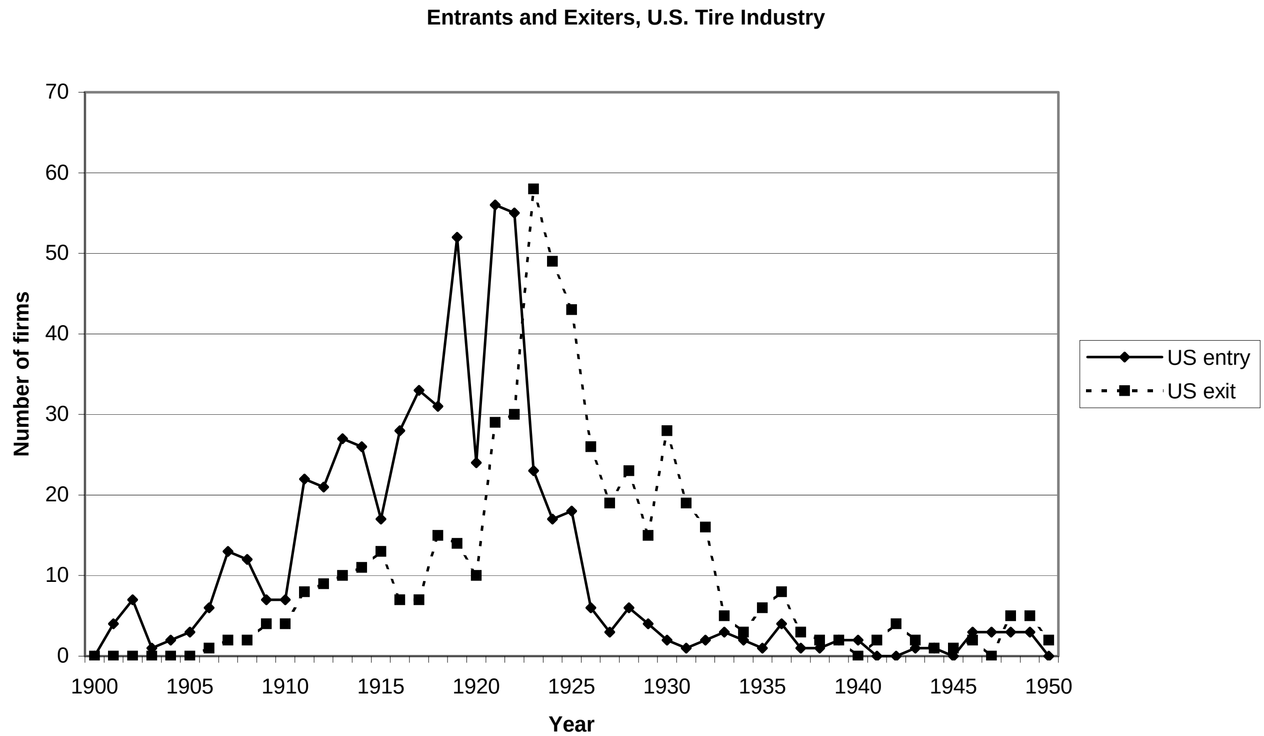
(Sources: Patent shares: own compilation based on *India Rubber World*, 1901-30; market shares: French, [1985, p. 470; 1991, p. 25, 47]; note: 1911-20 total market share estimated from French [1991, p 47])

Table 3: Exit Hazards of Tire Producers Listed in the 1920 *Tire Rate Book*

	Model 1	**Model 2**	**Model 3**
Cord tire producer	-.731*** (.203)		-.517** (.244)
Cord producer top size		-1.215*** (.432)	
Cord producer mid size		-.823* (.435)	
Cord producer small size		-.659 (.444)	
Non-cord producer top size		-.226 (.455)	
Non-cord producer mid size		-.270 (.470)	
Log age in 1920		-.256*** (0.122)	
No. of obs. (failures)	162 (128)	162 (128)	87 (74)
Log-likelihood	-519.937	-513.904	-280.252
P > chi^2	0.0006	0.0005	0.0391

Figure 1: Entry, Exit and the Number of Producers in the U.S. Tire Industry, 1901-1950

(Source: own compilation based on *Thomas' Register of American Manufacturers*)



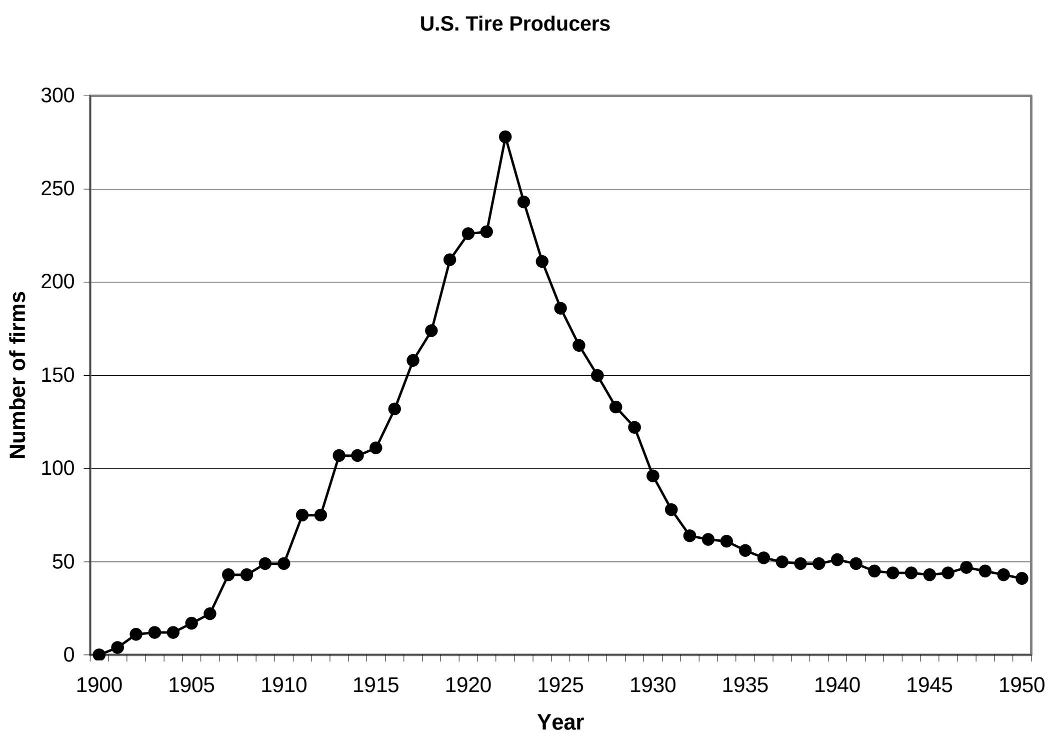


Figure 2: The Development of Tire Patents Over Time
(Source: own compilation based on *India Rubber World*, 1901-1930)

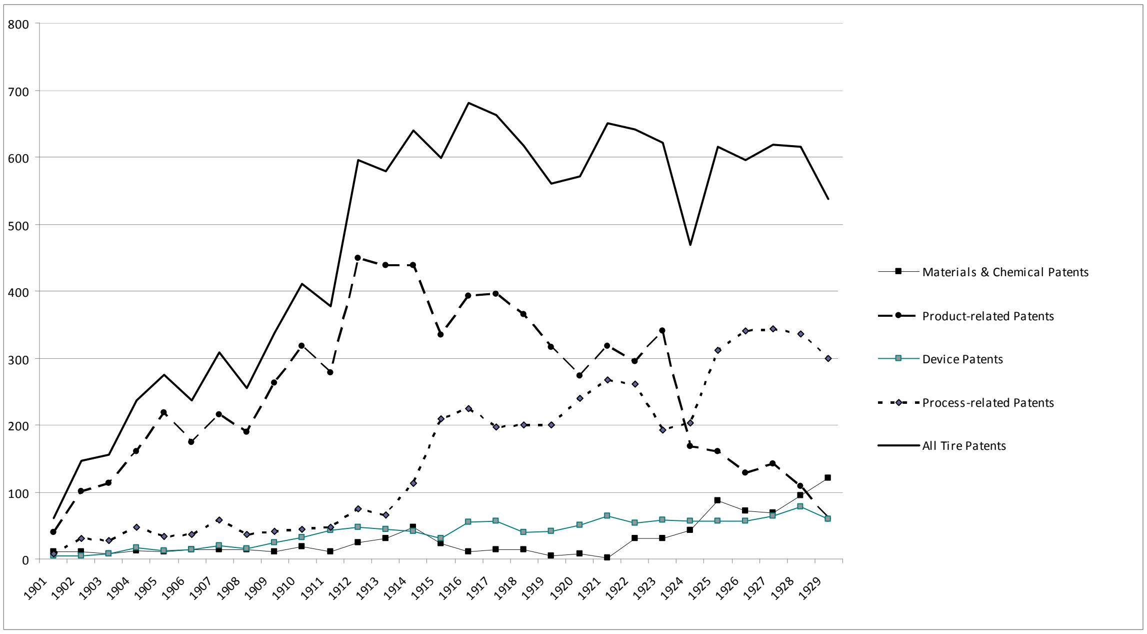
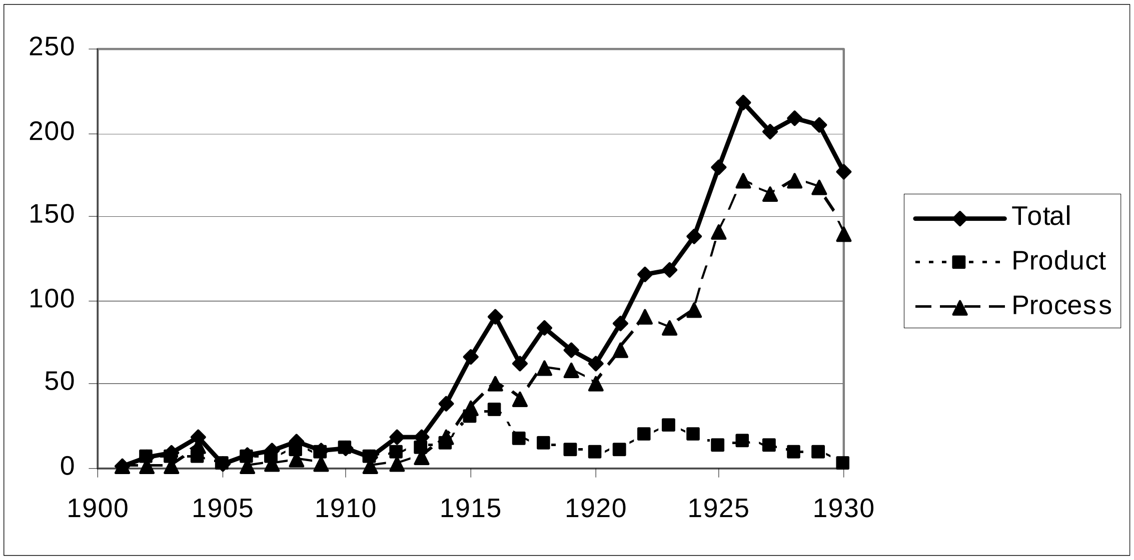


Figure 3: Patents Assigned to Tire Producers by Type and Year
(Source: own compilation based on *India Rubber World*, 1901-1930)



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